

Indoor intake fraction considering surface sorption of air organic compounds for life cycle assessment

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Abstract

Purpose Life cycle assessment (LCA) has largely focused on characterizing the impact of outdoor emissions. However, the intake fraction (iF) of indoor air emissions could be more important. The present paper aims to determine the long-term intake fractions of indoor emissions, including multiple indoor removal pathways such as sorption on indoor surfaces, and to compare it to the outdoor intake fraction.

Method The developed model accounts for the different removal pathways in buildings, including air exchange, degradation in the gas phase, degradation on surfaces, and finally partitioning between air, walls, and furniture assuming a kinetically limited material transfer between gas phase and a near-surface film. The indoor intake fraction is presented as a function of the adsorption and degradation rate on surfaces.

Results and discussion The intake fraction of volatile substances is only affected by the ventilation rate, with a constant intake fraction of 1×10^{-2} . For ozone-sensitive substances, indoor gas phase reactions can significantly reduce the intake

fraction. Semi-volatile substances are affected by the adsorption and degradation on room surfaces. For highly adsorbing substances, the decrease in intake fraction is limited to a minimum value of 2.5×10^{-4} by the mass transfer rate between air and room surfaces for a typical office or residence room in developed countries with temperate climate. Indoor intake fraction is compared to outdoor intake fraction calculated using the Impact 2002 multimedia model. Typical calculated indoor intake fraction values are in a significantly higher range (2.5×10^{-4} to 1×10^{-2}) than inhalation outdoor values (1×10^{-9} to 1×10^{-6}).

Conclusions This paper opens new possibilities to assess the health impact of indoor and outdoor air emissions in a consistent way, including surface sorption—a major removal pathway for semi-volatile compounds. By combining the newly calculated intake fractions with effect factors and with indoor and outdoor emissions per functional unit, it becomes possible to consistently account for indoor exposure in methods such as LCA

Keywords Human exposure · Indoor air · Indoor surfaces · Intake fraction · Life cycle impact assessment · Sorption · Ventilation

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Nomenclature

Symbol	Meaning	Dependent of	Unit
A_s	Total surface, projected area of the room	Room	Square meter
C_g^i	Indoor gas phase concentration in air for chemical i	Chemical	Kilograms per cubic meter
$C_{g,out}^i$	Outdoor gas phase concentration in air for chemical i	Chemical	Kilograms per cubic meter

$C_{s,n}^i$	Surface concentration for chemical i on surface n	Chemical and surface	Kilograms per square meter		Emission to indoor air per functional unit of chemical i		Kilograms per functional unit
$C_{b,n}^i$	Concentration of boundary layer including gaseous and particulate phase for chemical i on surface n	Chemical and surface	Kilograms per cubic meter	M_m^i	Emission to compartment m of the outdoor environment per functional unit of chemical i	Chemical	Kilograms per functional unit
$C_{gb,n}^i$	Gas phase concentration in boundary layer for chemical i on surface n	Chemical and surface	Kilograms per cubic meter	N_{pers}	Number of person in the room	Room	Person
D^i	Population-based human health impact per functional unit for chemical i	Chemical	Diseases cases per functional unit	\dot{S}^i	Source emission rate for chemical i	Chemical	Kilograms per hour
EF^i	Health effect factor for chemical i	Chemical	Disease cases per kilogram intake	TSP	Total suspended particulate concentration indoor	Room	Kilograms per cubic meter
				TSP _{out}	Total suspended particulate concentration outdoor	Independent	Kilograms per cubic meter
FU	Functional unit	Independent	Unitless	V_b	Volume of boundary layer	Room and surface	Cubic meter
h_m	Mass transfer coefficients from bulk air to the boundary layer and to the surface	Room	Cubic meters per square meter per hour	V_g	Volume of the room	Room	Cubic meter
				V_p^i	Vapor pressure for chemical i	Chemical	Atmosphere
h_c	Heat transfer coefficient by convection	Room	Watts per square meter per Kelvin	ϕ_p^i	Fraction adsorbed to particulate for chemical i	Chemical	Unitless
iF^i	Intake fraction for chemical i	Chemical	Kilograms intake per kilogram emitted				
iR	Individual inhalation rate	Independent	Cubic meters per hours per person				
k_{ex}	Air renewal rate	Room	per hour				
$k_g^{i,j}$	Second-order degradation rate constant in air with j species for chemical i	Chemical	Hours per parts per billion				
$k_{g,\text{deg}}^i$	Overall degradation rate in air for chemical i	Chemical	per hour				
$k_{s,\text{deg}}^i$	Overall degradation rate on surface for chemical i on surface	Chemical	per hour				
$k_{s,\text{net}}^i$	Equivalent net removal rate by sorption for chemical i	Chemical	per hour				
$k_{gb,\text{eq}}^i$	Equivalent removal rate for the transfer to boundary layer for chemical i	Chemical	per hour				
$k_{s,\text{eq}}^i$	Equivalent removal rate for the adsorption and degradation on the surface for chemical i	Chemical	per hour				
$K_{\text{eq},n}^i$	Partitioning coefficient between surface concentration and gas boundary layer concentration of surface type n for chemical i	Chemical and surface	Meter				
K_p^i	Partitioning coefficient between particulate concentration and gas concentration in the boundary layer for chemical i	Chemical	Cubic meters per kilogram				
M_{indoor}^i		Chemical					

1 Introduction

Several studies of the U.S. Environmental Protection Agency have identified indoor air pollution as one of the most important environmental risks to the nation's health (U.S. EPA 1987, 1990). The high risk from exposure to indoor air pollution reflects the (a) elevated concentrations of indoor contaminants, (b) the large number of people exposed to indoor air pollution, and (c) the fact that about 90 % of a person's time is spent in indoor locations (U.S. EPA 1995; Klepeis et al. 2001). Substantial efforts have been made since the mid-1980s to understand indoor pollutant behavior: Sanchez et al. (1987) determined emission rates of organic compounds from a floor adhesive, while others focused on the adsorption of gases (Renes et al. 1985) and organic substances present in indoor air to surface materials (Borazzo et al. 1990; Dunn and Tichenor 1988; Seifert and Schmahl 1987). Tichenor et al. (1991) applied a sink model based on Langmuir adsorption isotherms to test the behavior of two compounds on a carpet and Colombo et al. (1993) introduced a two-sink model. Besides adsorption to surfaces, degradation by chemical reactions could also affect the fate of substances emitted indoor. Atkinson and Arey (2003) measured a large number of reaction rates between volatile organic compounds (VOCs) and other gaseous reactants occurring in the gas phase. Lai et al. (2000) used a comparative approach to assess the individual indoor inhaled intake fraction and proposed a version including gas degradation. Their model includes removal processes occurring in the bulk air but does not take into account degradation in multiple compartments (air, carpet, and walls). Indeed, it is necessary to include surface degradation in new models

since a recent research has demonstrated that it could be an important removal pathway (Morrison 2008). Pommer compared modeled results with experimental measurement in the presence of co-reactants and suggested that the observed large deviations were partially due to the effect of surfaces, which were not included in the model (Pommer 2003; Pommer et al. 2004). This is especially important when considering long-term exposure to indoor emissions.

Given the importance of indoor pollutants, it is a weakness that most life cycle assessment (LCA) practices do not consider their impacts. Neglecting the impact of indoor pollutant in LCA may result in overlooking the health impacts to workers in the production phase and to indoor users in the use phase during a product or process's life cycle. Fortunately, supported by the rapid development of indoor pollutant behavior research, several case studies have addressed the indoor emission's impact in an LCA perspective (Hellweg et al. 2005; Kikuchi and Hirao 2008, 2010). Most recent LCA developments use the concept of intake fraction (iF) as a simple and effective metric for comparative risk assessment to quantify the fraction of an emission which is taken in by an entire population (Bennett et al. 2002a). It has been applied to assess outdoor emissions, often using multimedia models (Bennett et al. 2002b; Levy et al. 2003; Marshall et al. 2003; Zhou et al. 2003; Margni et al. 2004; Pennington et al. 2005) and can also be applied to indoor air. Evans et al. (2002) reviewed studies determining intake fraction, giving the first hints that intake fraction can be significantly higher indoors than outdoors. Combined with effect data, one can determine characterization factors used to rank harmful emissions (Crettaz et al. 2002; Pennington et al. 2002). Meijer et al. (2005) characterized the impact of indoor pollutants in typical Dutch dwellings based on airflows and confirmed the health damages of indoor emissions are as important as the rest of the life cycle of the same dwelling. The joint efforts within the UNEP/SETAC Life Cycle Initiative developed a general framework of assessing intake fraction of indoor pollutant emissions with a one-box model and showed that the indoor intake fraction is substantially higher than outdoor intake fraction (Hellweg et al. 2009). However, these improvements in characterizing the impacts of indoor pollutant emission still lack the consideration of adsorption to surfaces (e.g., carpet, wall, furniture, etc.) and oxidation reactions with radical species found indoors. Weschler and Nazaroff (2008) discussed various removal pathways and sorptive partitioning to organic matter on fixed surfaces and on airborne particles in a dynamic model. This is very useful to complement the impact assessment of indoor pollutant emissions but needs further adjustments to be included in a general LCA framework.

There is therefore a need to calculate long-term intake fraction including all main removal mechanisms and to

compare it with outdoor emissions. The following questions need to be addressed:

1. How can long-term indoor intake fractions as a function of ventilation rate and of degradation rates in the gas phase and on surfaces, including furniture, walls, and carpets, be modeled?
2. How does the adsorption and degradation on surfaces influence the intake fraction and for which type of chemicals is this an especially relevant phenomena?
3. What is the relative magnitude of indoor versus outdoor intake fractions as a function of key chemical properties?

To answer these questions, the present paper briefly reviews the principles governing the fate of a substance in an indoor environment, identifying the most likely values for parameters governing indoor inhalation intake. On the basis of adapted mass balances, an original indoor air quality model that includes bulk air to surface transport and surface degradation is proposed, allowing the estimation of long-term intake fractions for indoor emissions. Then, we assess and discuss the sensitivity of the model to key parameters such as air exchange rate and degradation rates on surfaces. Finally, indoor intake fraction is compared to outdoor intake fraction calculated using the Impact 2002 model (Pennington et al. 2005).

2 Methods

2.1 Fate and removal pathways of substances in indoor environments

The removal of a substance from a typical indoor environment mainly occurs through three major pathways (Fig. 1): (a) air exchange, (b) reaction with oxidizing chemicals, and (c) sorption and degradation on room surfaces. Each removal pathway has been quantitatively assessed to provide consistent values with international standards or common average situations (see supporting information supplement S1 for a more detailed discussion and literature used):

1. *Removal by air exchange:* An average air renewal rate of $k_{\text{ex}} = 0.68 \text{ h}^{-1}$ is used as an average value for temperate climates with relatively tight dwellings (ASHRAE 2003). The value of 0.68 was back calculated from personal ventilation rate and the indoor volume per person. A personal ventilation rate of $50 \text{ m}^3 \text{ pers}^{-1} \text{ h}^{-1}$ is taken as a recommended value from ASHRAE (2003) and the typical indoor volume per person given by ASHRAE (2003) amounts to $73.5 \text{ m}^3 \text{ pers}^{-1}$.
2. *Elimination by reactions with oxidizing chemicals, mainly ozone, hydroxyl radicals, and nitrate radicals (gas phase degradation):* Second-order degradation rate constants (k_g^{ij} , in hours per parts per billion) used for the

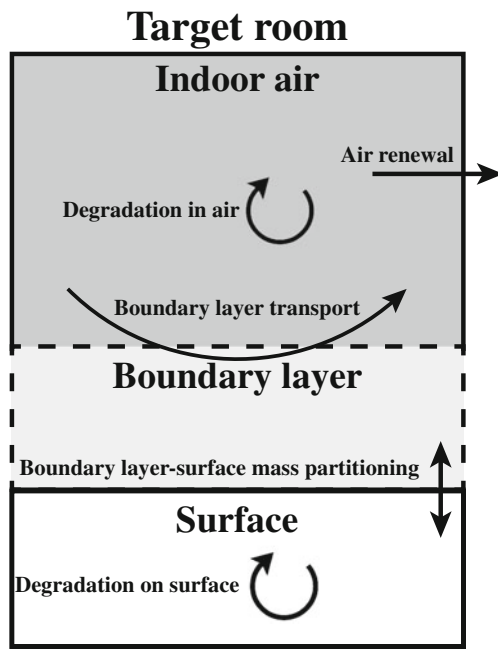


Fig. 1 Main removal pathways affecting the gas phase concentration

calculations were principally extracted from Atkinson and Arey (2003) and Nazaroff and Weschler (2004). When not available, additional values were collected using the EPI Suite v3.12 software (U.S. EPA 2004). Long-term averaged values of ozone ($[O_3]=8$ ppb), the hydroxyl radical ($[OH]=3 \times 10^{-6}$ ppb), and the nitrate radical ($[NO_3]=10^{-3}$ ppb) were used, yielding for the overall removal rate by reaction: $k_{g,deg}^i = k_g^{i,OH} \cdot [OH] + k_g^{i,O_3} \cdot [O_3] + k_g^{i,NO_3} \cdot [NO_3]$. This degradation rate only applies to the gas phase, to ensure consistency with the outdoor modeling.

3. *Net removal rate from the air to the surface:* This net removal rate results from three successive processes in series: (a) transfer from the air to the boundary layer, (b) partitioning between the air boundary layer and the room surfaces and furniture, and (c) degradation at surfaces. These processes are described below:

- (a) *Boundary layer transport:* In most practical situations, transfer to the surface is controlled by convective and diffusive transport since the adsorption step is practically instantaneous (Axley 1991). Mass transfer coefficients from bulk air to the boundary layer and to the surface, h_m [in cubic meters per square meter per hour], have been estimated here using heat transfer coefficients by convection h_c [in watts per square meter per Kelvin] according to the heat and mass transfer analogy (Axley 1991). A mean heat transfer by convection value of $3 \text{ W m}^{-2} \text{ K}^{-1}$ which is representative for the average long-term behavior of building in

different areas according to ASHRAE (2003) and ISO (2004) has been selected, leading to an air convection flux of $8.8 \text{ m}^3 \text{ m}^{-2} \text{ h}^{-1}$.

- (b) *Boundary layer-surface mass partitioning:* Exchanges are supposed to be fast close to the surface and the gas and the particle phases in the boundary layer are assumed to be in equilibrium with the surface:

$$K_{eq,n}^i = \frac{C_{s,n}^i}{C_{b,n}^i} [m]$$

where

$$C_{b,n}^i = C_{gb,n}^i (1 + K_p^i \cdot \text{TSP}). \quad (1)$$

The gas boundary layer is characterized by a specific gas concentration $C_{gb,n}^i$ [in kilograms per cubic meter] and $C_{s,n}^i$ [in kilograms per square meter] is the surface concentration considering the horizontally projected area (as opposed to the true area that account for interior pores and irregularities—Won et al. 2000). $C_{b,n}^i$ [in kilograms per cubic meter] is the concentration of the boundary layer including gaseous and particulate phase. The fraction adsorbed to particles assumes equilibrium between gas and particulate phases and is determined from the partition coefficient between particulate and gas (K_p^i [in cubic meters per gram]) multiplied by the total suspended particulate indoor (TSP [in grams per cubic meter]). Research done by Won et al. (2000, 2001) show that the logarithm of the partitioning coefficient ($K_{eq,n}^i$ [in meters]) is correlated with the logarithm of the saturation vapor pressure (V_p^i [atmosphere], ranged from 10^{-1} to 10^{-4} atm.). $K_{eq,n}^i$ is specific for each surface and is given for the two following types of surfaces representing the low- and high-specific area surfaces in indoor environment: Virgin gypsum board:

$$\log(K_{eq,vgb}^i) = -0.74 \times \log(V_p^i) - 1.94. \quad (2)$$

Carpet with pad:

$$\log(K_{eq,cwp}^i) = -0.81 \times \log(V_p^i) - 1.15. \quad (3)$$

Depending on the respective concentration in air and on the surface, the partitioning behavior of chemicals between surfaces and the boundary layer will lead either to adsorption on the surfaces (the typical situation at steady state, for a constant indoor emission as studied in this paper) or desorption from surfaces (dynamic changes in concentration or releases from walls). At steady state, assuming a

constant indoor source, the net resulting flux will correspond to an adsorption on the surfaces followed by degradation on the surface.

- (c) *Surface degradation*: Recent research has revealed that surface degradation could be an important factor in closed, low ventilated spaces (Weschler et al. 2007; Coleman et al. 2008). However, there is little quantitative information available on the exact degradation rates on surfaces that may depend on concentration of oxidizing chemicals and their reaction rates with organic compounds (Morrison 2008). As a first pragmatic approximation, a generic surface degradation constant $k_{s,deg}^i$ [in per hour] has been approximated here by a fixed fraction of 10 % of the degradation rates in gas phase $k_{g,deg}^i$ [in per hour], assuming that radical species in the air are responsible for the degradation in the surface. Since this rate is not available in empirical studies, a sensitivity study is presented at the end of the results section, using values of the surface degradation rate varying broadly from 1 % up to 100 % of the degradation rate in gas phase.

Detailed information on the discussion and literature used for these difference exchanges are given in supplement S1 including S1.1 Air exchange, S1.2 Gas phase degradation, S1.3 Boundary layer transport and gas-surface mass partitioning, and S1.4 Surface degradation.

2.2 Model description and scenario definition

2.2.1 Model description

The inhalation intake fraction of a pollutant emitted indoors can be defined as the mass fraction of the chemical released in a specific indoor location that is taken in by its occupants via inhalation. The general definition of intake fraction given by Bennett et al. (2002b) is:

$$iF = \frac{\sum_{\text{people,time}} \text{intake of pollutant by an individual (mass)}}{\text{mass released into the environment}} \quad (4)$$

We are interested in the long-term behavior, which is the time-integrated intake fraction of a given emission. For a linear model, this corresponds to the intake fraction at steady state, assuming a continuous emission source. The intake fraction by inhalation is proportional to quantity of air inhaled by the inhabitants in a room and is given by:

$$iF_{\text{indoor}}^{\text{inhalation}} = \frac{C_g^i \cdot (1 + K_p^i \cdot \text{TSP}) \cdot iR \cdot N_{\text{pers}}}{\dot{S}^i} \quad (5)$$

with C_g^i [in kilograms per cubic meter] the averaged gas phase concentration of a pollutant, K_p^i [in cubic meters per

gram] the partition coefficient between particulate and air, TSP [in grams per cubic meter] the total suspended particulate indoor, N_{pers} the number of persons in a room, iR [in cubic meters per hour per person] the individual inhalation rate, and \dot{S}^i [in kilograms per hour] a single source emission rate.

The mass balance equation of the substance in the bulk gas phase at steady state can be expressed as the emission source \dot{S}^i into air minus the three different removal pathways described in the previous section, (i.e., exchange with outdoor environment, overall degradation in the gas phase, and net mass transport from the bulk to the thin layer in contact with the surface. The exchange with outdoor environment comprises outflow to outdoor and inflow from outdoor. However, the outdoor concentration is supposed to be negligible for the selected products in this paper):

$$V_g \frac{d(C_g^i \cdot (1 + K_p^i \cdot \text{TSP}))}{dt} = \dot{S}^i - k_{\text{ex}} \cdot V_g \cdot (C_g^i \cdot (1 + K_p^i \cdot \text{TSP}) - C_{g,\text{out}}^i \cdot (1 + K_p^i \cdot \text{TSP}_{\text{out}})) - k_{g,deg}^i \cdot C_g^i \cdot V_g - h_m \cdot A_{s,n} \cdot (C_g^i - C_{gb,n}^i) \cdot (1 + K_p^i \cdot \text{TSP}) \quad (6)$$

$k_{g,deg}^i$	Total degradation rate in gas phase [in per hour]
k_{ex}	Air renewal rate [in per hour]
h_m	Mass transfer coefficient [in cubic meters per square meter per hour]
V_g	Volume of the room [in cubic meter]
$A_{s,n}$	Total surface, projected area [in square meter]
$C_{gb,n}^i$	Concentration in the boundary layer [in kilograms per cubic meter]
$C_{g,\text{out}}^i$	Outdoor concentration, supposed to be negligible for selected products [in kilograms per cubic meter]
TSP_{out}	Outdoor total suspended particulate [in grams per cubic meter]

This mass balance equation does not differ fundamentally from those commonly used to predict gas concentrations in inert test chambers, but adds specific terms for the degradation pathways and for mass transfer dynamics. A similar mass balance can be written for the room surfaces, grouping the boundary layer with the surface. In this case, the total variation of mass in the boundary layer and on surface is given by the net flux of materials carried by the air to the layer minus the degradation of chemicals on surfaces:

$$A_{s,n} \frac{dC_{s,n}^i}{dt} + V_{b,n} \frac{d(C_{gb,n}^i \cdot (1 + K_p^i \cdot \text{TSP}))}{dt} = h_m \cdot A_{s,n} \cdot (C_g^i - C_{gb,n}^i) \cdot (1 + K_p^i \cdot \text{TSP}) - k_{s,deg}^i \cdot C_{s,n}^i \cdot A_{s,n} \quad (7)$$

Assuming that the surface and air boundary layer are in equilibrium for the sum of particle and gas phase, Eq. 1 can be used to replace $C_{gb,n}^i \cdot (1 + K_p^i \cdot \text{TSP})$ by $C_{s,n}^i / K_{eq,n}^i$ in both mass balance (Eqs. 6 and 7). Solving this system at steady state allows determining the specific concentrations in the gas phase (C_g^i) and on surfaces ($C_{s,n}^i$):

$$C_g^i \cdot (1 + K_p^i \cdot \text{TSP}) = \frac{\dot{S}^i}{k_{ex} \cdot V_g + k_{g,deg}^i \cdot V_g \cdot (1 - \varphi_p^i) + h_m \cdot A_{s,n} \cdot \frac{k_{s,deg}^i \cdot K_{eq,n}^i}{k_{s,deg}^i \cdot K_{eq,n}^i + h_m}} \quad (8)$$

where $\varphi_p^i = \frac{K_p^i \cdot \text{TSP}}{(1 + K_p^i \cdot \text{TSP})}$ is the fraction of the chemical adsorbed to particulate and

$$C_{s,n}^i = C_g^i \cdot (1 + K_p^i \cdot \text{TSP}) \frac{h_m \cdot K_{eq,n}^i}{k_{s,deg}^i \cdot K_{eq,n}^i + h_m}. \quad (9)$$

Surface-specific partition coefficients and areas have to be accounted for in case of multiple types of surfaces. The generalization to this case and its complete demonstration is available in the supporting information, supplement S2.

Introducing these developments in Eq. 5 leads to:

$$iF_{indoor}^{inhalation} = \frac{iR \cdot N_{pers}}{V_g \cdot (k_{ex} + k_{g,deg}^i \cdot (1 - \varphi_p^i) + k_{s,net}^i)} \quad (10)$$

where the equivalent net removal rate by sorption is given by:

$$k_{s,net}^i = \sum_n \left(\frac{1}{\frac{1}{A_{s,n} \times h_m / V_g} + \frac{1}{A_{s,n} \cdot k_{s,deg}^i \cdot K_{eq,n}^i / V_g}} \right) = \sum_n \left(\frac{1}{\frac{1}{k_{gb,eq}^i} + \frac{1}{k_{s,eq}^i}} \right). \quad (11)$$

Therefore, the intake fraction depends on the ventilation removal rate per person plus two removal rates due to degradation in the gas phase as well as degradation on surfaces. Equation 11 shows that this latter term is itself the combination of two equivalent removal rates in series: one for the transport to the surface boundary layer ($k_{gb,eq}^i$ [in per hour]) that is independent of chemical properties and one for the adsorption and the degradation on the surface ($k_{s,eq}^i$ [in per hour]) that is chemical specific. An additional term representing removal by human uptake could be added to this equation denominator but is in general negligible.

2.2.2 Scenario definition

To identify the key parameters determining the intake fraction, the model is applied to the indoor conditions summarized in

Table 1 and to 73 chemicals commonly found indoors, with a focus on four representative chemicals (Table 2, see Electronic Supplementary Material supplement S3 for list and properties of all chemicals). This scenario is representative for a room with closed windows and an air renewal rate of 0.68 h^{-1} . The model can easily be adjusted to other conditions to be representative of a specific target population or situation.

3 Results

3.1 Indoor intake fractions

This section analyzes the model results for the selected chemicals, identifying the key parameters affecting the intake fraction. Figure 2 plots the intake fraction as a function of the main chemical-specific parameter affecting Eqs. 10 and 11, that is, the adsorption and the degradation on the surface $k_{s,eq}^i$ with the units in hours. These rates can directly be compared to the air exchange rate. One can distinguish three main groups of different intake fractions (see Fig. 2) and four main different behaviors of various chemicals (see Fig. 2):

1. In the first group, the intake fractions are nearly constant, with a maximum value of 1×10^{-2} , corresponding to a removal dominated by air exchange.
2. In this group as well as in the second one, the intake fractions of a few substances significantly affected by gas degradation (e.g., cyclohexene) are observed below the main baseline.
3. In the center group, surface adsorption and degradation start to play a significant role and lead to a sharp decrease in intake fractions. As could be expected from Eq. 10, when the equivalent removal rate by surface adsorption reaches the average exchange rate of 0.68 h^{-1} , half of the chemical is removed by advection and half by sorption and degradation.
4. In the third group, the decrease in intake fractions is limited by the advective mass transfer from the bulk to the surface and the intake fractions reach a lower limit of approximately 2.4×10^{-4} .

To better understand these different behaviors, four substances identified in Fig. 2 and described in Table 2 are selected as characteristic of each pattern and are discussed in more detail:

1. Volatile and/or persistent substances mostly affected by ventilation removal (group I)

For volatile chemicals such as benzene, toluene, or formaldehyde, the adsorption and degradation removal rate ($1.0 \times 10^{-5} \text{ h}^{-1}$ for benzene) is low and negligible compared

Table 1 Main selected parameters for typical indoor conditions

Parameters	Typical value	Unit	Source
Air renewal rate, k_{ex}	0.68	per hour	ASHRAE (2003) ^a
Breathing rate, iR	0.5	Cubic meters per hour per person	Layton (1993) ^b
Mass transfer coefficient, h_m	8.8	Cubic meters per square meter per hour	ISO 6946:1996 (2004)
Area per volume (carpet), $A_{s,n}/V_g$	0.41	Square meter per cubic meter	Adapted from Singer et al. (2002)
Area per volume (total), $A_{s,n}/V_g$	2.7	Square meter per cubic meter	Adapted from Singer et al. (2002)
[OH] indoors	3×10^{-6}	Parts per billion by volume	See supporting info. (Suppl. 1)
[O ₃] indoors	8	Parts per billion by volume	See supporting info. (Suppl. 1)
[NO ₃] indoors	10^{-3}	Parts per billion by volume	See supporting info. (Suppl. 1)

^a The value of 0.68 was back calculated from personal ventilation rate and the indoor volume per person. A personal ventilation rate of $50 \text{ m}^3 \text{ pers}^{-1} \text{ h}^{-1}$ is taken as a recommended value from ASHRAE (2003) and the typical indoor volume per person given by ASHRAE (2003) amounts to $73.5 \text{ m}^3 \text{ pers}^{-1}$

^b The volume of air breathed daily is taken as $iR=0.5 \text{ m}^3 \text{ h}^{-1}$, that is, the average of the lifetime average values for males ($0.58 \text{ m}^3 \text{ h}^{-1}$) and females ($0.42 \text{ m}^3 \text{ h}^{-1}$) according to Layton (1993)

to the air exchange rate of 0.68 h^{-1} that dominates the removal process. The total contribution of gas phase degradation is also restricted and does not exceed 0.05 % of the total removal rate. Both degradation in the gas phase and the equivalent net removal rate by sorption are therefore too small to compete with air ventilation in terms of substance removal. Calculating the limiting case, i.e., when $k_{s,\text{net}}^i$ tends

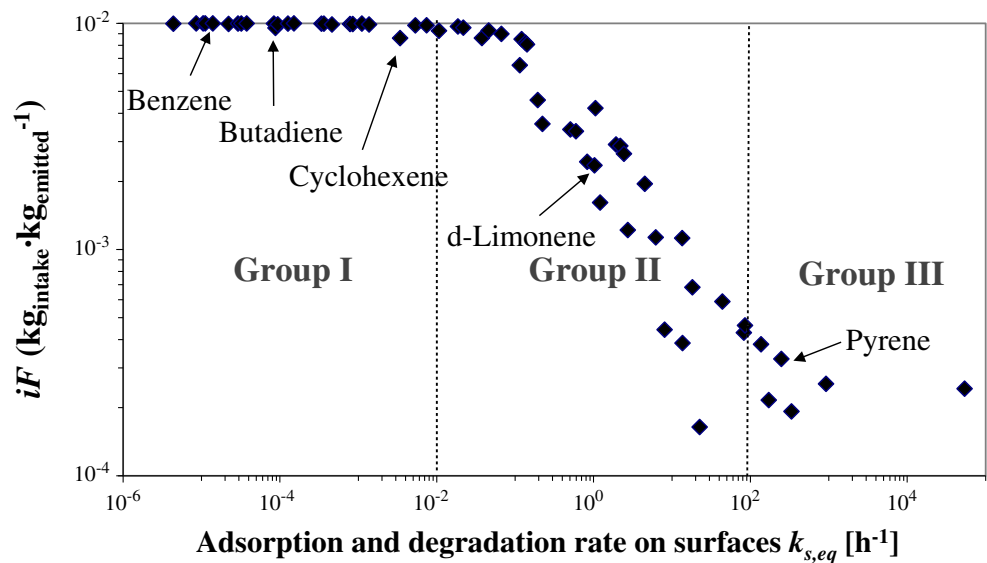
to 0 in Eq. 10, yields the intake fraction when dominated by air exchange:

$$iF_{\text{indoor}}^{\text{max}} = \frac{iR \cdot N_{\text{pers}}/V_g}{k_{\text{ex}} + k_{g,\text{deg}}^i(1 - \phi_p^i)} \cong \frac{iR \cdot N_{\text{pers}}/V_g}{k_{\text{ex}}} = \frac{0.5/73.5}{0.68} = 1 \times 10^{-2}. \quad (12)$$

Table 2 Chemical properties of discussed organic compounds

Substances	Group I		Group II	Group III
	Benzene	Butadiene	d-Limonene	Pyrene
ID#	13	22	51	70
CAS #	71-43-2	106-99-0	5989-27-5	129-00-0
Chemical properties				
Degradation rate for $\cdot\text{OH}$: $k_{g,\text{deg}}^{\text{OH}}$ [in per hour] at 3×10^{-6} ppbv OH	3.5×10^{-4}	1.8×10^{-2}	4.5×10^{-2}	13×10^{-2}
Degradation rate for O ₃ : $k_{g,\text{deg}}^{\text{O}_3}$ [in per hour] at 8 ppbv O ₃	5.0×10^{-8}	5.7×10^{-3}	1.5×10^{-1}	N/A
Degradation rate for $\cdot\text{NO}_3$: $k_{g,\text{deg}}^{\text{NO}_3}$ [in per hour] at 10^{-3} ppb NO ₃	N/A	8.9×10^{-3}	1.1	N/A
Degradation rate in gas phase: $k_{g,\text{deg}}^i$ [in per hour]	3.5×10^{-4}	3.2×10^{-2}	1.3	1.3×10^{-2}
Degradation rate on surface: $k_{s,\text{deg}}^i$ [in per hour] (10 % of $k_{g,\text{deg}}^i$)	3.5×10^{-5}	3.2×10^{-3}	1.3×10^{-1}	1.3×10^{-3}
Molecular weight: MW [in dalton]	78.1	54.1	136.2	202.3
Vapor pressure: V_p^i [atmosphere] at 25°C	0.12	2.8	1.9×10^{-3}	5.9×10^{-9}
Partition coefficient for carpet: $K_{\text{eq,carpet}}^i$ [in meters]	3.7×10^{-1}	2.7×10^{-2}	12	5.3×10^5
Partition coefficient for gypsum board: $K_{\text{eq,gypsum board}}^i$ [in meters]	6.2×10^{-2}	4.6×10^{-3}	1.2	8.8×10^4
Removal rates (denominator Eq. 10)				
Air exchange: k_{ex} [in per hours]	0.68	0.68	0.68	0.68
Gas degradation: $k_{g,\text{deg}}^i$ [in per hour]	3.5×10^{-4}	3.2×10^{-2}	1.3	1.3×10^{-2}
Equivalent net removal rate by sorption: $k_{s,\text{net}}^i$ [in per hour]	1.0×10^{-5}	8.8×10^{-5}	0.93	20
Transport to surface boundary layers: $k_{gb,\text{eq}}^i$ [in per hour]	27	27	27	27
Adsorption and degradation on surfaces: $k_{s,\text{eq}}^i$ [in per hour]	1.0×10^{-5}	8.8×10^{-5}	1.0	2.5×10^2
Indoor intake fraction [kilograms intake per kilogram emitted]	1×10^{-2}	9.6×10^{-3}	2.4×10^{-3}	3.3×10^{-4}
Outdoor intake fraction [kilograms intake per kilogram emitted]	1.3×10^{-6}	4.6×10^{-7}	N/A	3.4×10^{-6}
Inhalation oral	9.9×10^{-10}	2.6×10^{-11}	N/A	5.7×10^{-4}

Fig. 2 Modeled intake fraction for 73 indoor chemicals as a function of $k_{s,eq}^i$ the equivalent removal rate due to surface adsorption and degradation from Eq. 11, namely, the sum for the wall, furniture, and carpet of the product of surface degradation rate ($k_{s,deg}^i$), partition coefficient ($K_{eq,n}^i$), and surface area per unit volume ($A_{s,n}/V_g$)



The results for these substances in a constant high intake fraction of 1 % (iF^{\max}) correspond to the case with negligible degradation. The relevant parameters in this case are therefore the intake rate per person (iR) and the ventilation rate per person, in agreement with the model of Lai et al. (2000).

2. Ozone or OH-sensitive substances affected by gas degradation (groups I and II)

Butadiene is also located in group I, but its chemical properties are quite different from benzene. The two double carbon–carbon bonds of the butadiene molecule make it sensitive to reactions with ozone and hydroxyl radical ($k_{g,deg}^i = 2.4 \times 10^{-2} \text{ h}^{-1}$) leading to respectively aldehydes and alcohols as secondary products. For butadiene, the gas degradation term of Eq. 10 corresponds to a removal rate of $3.2 \times 10^{-2} \text{ h}^{-1}$ (see Table 2), compared to the air renewal of 0.68 h^{-1} and therefore contributes to 4.6 % of the total removal.

3. Substances with reduced intake fraction due to adsorption and degradation rate (group II)

The second group is delimited by a removal rate from surface adsorption and degradation between 0.01 and 100 h^{-1} : the increasing adsorption starts competing with ventilation and leads to a fall in intake fraction. For d-limonene, sorption and degradation lead to a removal rate of 1.0 h^{-1} (see Table 2) which is larger than the air renewal and represents 34 % of the total removal against 22 % for air exchange. Since d-limonene contains two double bonds, the degradation in the gas phase is also important and represents 44 % of the total losses. This results in a reduced intake fraction of 2.4×10^{-3} . In this central group, the removal rate for adsorption and degradation (1.0 h^{-1}) is an important

factor that controls the ability of the chemical to deposit on surfaces, as it is significantly lower than the transport rate to the boundary layer (27 h^{-1}).

In this middle group, the intake fraction can be approximated by:

$$iF_{\text{indoor}}^{\text{intermediary}} \cong \frac{iR \cdot N_{\text{pers}}/V_g}{k_{\text{ex}} + k_{g,deg}^i(1 - \varphi_p^i) + \sum_n A_{s,n} \cdot k_{s,deg}^i \cdot K_{eq,n}^i/V_g}$$

$$= \frac{\overbrace{0.5/73.5}^{\text{ford-limonene}}}{0.68 + 1.3 + 1.0} \cong 2.4 \times 10^{-3}. \quad (13)$$

The dominant parameters are the partition coefficient $K_{eq,n}^i$, that is chemical and surface dependent, the gas phase degradation rate $k_{g,deg}^i$, and the degradation rate on surface $k_{s,deg}^i$, which is chemical dependent and competes with the air exchange removal.

4. Strongly adsorbed substances, with intake fraction reduction limited by the mass transfer between air and room surfaces (group III)

Once removal rate by adsorption and degradation on surfaces further increases above the airflow rate entering surface boundary layers (27 h^{-1}), removal by surfaces becomes controlled and limited by this airflow. The main characteristic of the chemicals located in this group is that they are entirely trapped and degraded on surfaces once they have reached it. For example, pyrene has a very low vapor pressure ($5.9 \times 10^{-9} \text{ atm.}$), which is so low that it is irretrievably caught in materials when the air flux contacts the surface. Considering our scenario, the air flux to surfaces represents about 40 times the export by ventilation. In this

case, the convective air flux along surfaces is the main parameter affecting and limiting the decrease in intake fraction; therefore, the intake fraction becomes independent of other chemical properties and is equal to:

$$iF_{\text{indoor}}^{\text{min}} = \frac{iR \cdot N_{\text{pers}}/V_g}{k_{\text{ex}} + k_{g,\text{deg}}^i(1 - \phi_p^i) + \sum_n A_{s,n} \cdot h_m/V_g}$$

$$\cong \frac{iR \cdot N_{\text{pers}}/V_g}{\sum_n A_{s,n} \cdot h_m/V_g} = \frac{0.5/73.5}{27} \cong 2.5 \times 10^{-4} \quad (14)$$

where iF^{min} is the minimum theoretical intake fraction value once convective flow to surfaces is limiting.

As a first evaluation, a comparison between the intake fraction obtained in this study and exposure-relevant emission factors (EREFs) measured by Singer et al. (2002) was carried out to assess the results of the model for two different furnishing levels and taking into account absorption. It shows that the relative change in intake fraction due to absorption is well correlated to the relative change in observed EREF confirming that sorption phenomena are properly represented by the developed model (for detailed results, see Electronic Supplementary Material, supplement S4).

3.2 Comparison between indoor and outdoor intake fractions

As discussed in Eq. 15 in the next section below, the health impact from emissions depends both on indoor and outdoor intake fractions and on quantity emitted. It is nevertheless interesting to have a first comparison based on intake fractions in order to put indoor exposure in perspective. Figure 3 compares the modeled indoor intake fractions with outdoor intake fractions calculated using the Impact 2002 multi-pathway model (Margni et al. 2004; Pennington et al. 2005). (For the names of numbered compounds, see supporting information, supplement S3; for

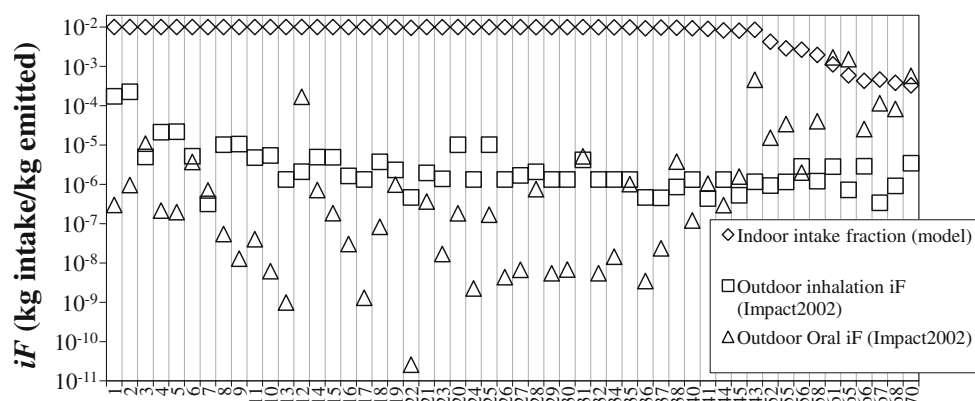
detailed description, see Electronic Supplementary Material, supplement S5).

The intake fractions are up to three orders of magnitudes higher inside than outside for almost all chemicals. Substances located on the left of the Fig. 3 have a relatively higher outdoor inhalation intake fraction due to exceptional persistence and volatility frequently encountered in small chlorinated compounds such as trichloromethane (chloroform, #2) and tetrachloromethane (carbon tetrachloride, #1). The ratio between indoor/outdoor inhalation intake fractions varies from 44 (1,1,1-trichloroethane, #2) to 3.1×10^4 (formaldehyde, #7) with an average of 5.8×10^3 . For chemicals with low vapor pressures, located on the right hand of Fig. 3, in parallel to increasing sorption on surfaces, bioaccumulation in the food chain becomes a relevant process and is responsible for the increasing oral intake fraction. In this case, oral intake fraction increases up to a range of 1×10^{-3} to 1×10^{-2} , as also observed by Bennett et al. (2002a).

4 Discussion and sensitivity analysis

The present model has been used to evaluate the long-term indoor intake fraction as a function of ventilation rate, degradation rates in gas, and surface removal, enabling the identification of key parameters and chemical properties affecting indoor intake fraction. It has also shown that intake fraction is generally about three orders of magnitude higher indoor than outdoors, indicating the importance of providing methods to fully account for indoor emissions in life cycle assessment or in other methods considering long-term impacts. This finding also means that the outdoor impacts via inhalation on human health of an indoor emission are generally negligible compared to indoor impacts. However, oral intake from outdoor emission could still be important for compounds with low vapor pressures. A full comparison between indoor and outdoor emission cannot, however, be solely based on intake fractions, but needs to consider the

Fig. 3 Comparison of the indoor intake fraction by inhalation with the inhalation and oral intake fractions for outdoor emissions to air for 52 out of a total of 73 substances. Substances are ordered by decreasing vapor pressures (see Electronic Supplementary Material, supplement S3 for chemical names and CAS numbers)



respective magnitude of emissions to indoor air and to outdoor environmental compartment m per functional unit (M_{indoor} and M_m , [in kilograms per functional unit]). It also needs to account for the respective toxicity and effect factors of pollutants emitted indoors and outdoors (\overline{EF}^i , in disease cases per kilogram intake or DALY per kilogram intake). Whereas a full case study is beyond the scope of the present paper, the integration of the intake fraction in the LCA framework can be qualitatively discussed. Building on Rosenbaum et al. (2011), the population-based human health impact per functional unit [disease cases per functional unit or DALY per functional unit] is given by:

$$D = \sum_i \left[\overline{EF}^i \cdot (\overline{iF}_{\text{indoor}}^i \cdot M_{\text{indoor}}^i + \sum_m \overline{iF}_m^i \cdot M_m^i) \right]. \quad (15)$$

The generally lower outdoor intake fraction means that for a given pollutant, as soon as indoor life cycle emissions per functional unit are higher than 1/1,000 of the outdoor one, the indoor emissions matter and need to be considered as a potentially significant impact. The influence of several hypotheses needs to be addressed in sensitivity studies to test the model robustness and are further discussed below.

Air exchange rate Simulations have been made in order to assess the sensitivity of the model to ventilation and degradation rates. Figure 4 gives intake fraction variations caused by different ventilation rates selected within common values found in literature. It has been obtained assuming that ventilation is completely independent of others parameters. However, convection on wall could be correlated with the air ventilation rate, especially at high ventilation rates like opened windows. This would tend to increase the removal

by ventilation and surface adsorption and degradation which lead to a strong decrease of the indoor intake fraction.

Since the intake fractions are directly proportional to the ventilation rate per person, increasing ventilation rates while keeping the number of exposed persons constant reduces the maximum intake fraction value for volatile chemicals (groups I and II of Fig. 2). The removal rate on surfaces remains significant and reduces intake fraction for highly adsorbing and degrading chemicals because of the high airflow rate entering the boundary layer ($\sim 27 \text{ h}^{-1}$). This reduction would be even more significant if considering the increase in indoor advection linked to an increase in air exchange rate.

Degradation on surfaces Due to the scarcity of data, baseline degradation rates on surfaces were set at 10 % of the gas phase degradation rate and are subject to large uncertainties. While varying degradation on surfaces up to two orders of magnitude (from 1 % up to 100 % of the gas phase degradation rate), Fig. 5 shows that it is only for the group II chemicals that $k_{s,\text{deg}}$ directly affects the intake fraction (see Eq. 12) and leads to high variation in intake fraction. Efforts to measure these degradation rates on surfaces should therefore be focused on substances within or close to that group. This parameter has little influence either for volatile substances for which the air exchange rate dominates and leads to a constant intake fraction of 1×10^{-2} (Eq. 12) or for highly adsorbing and degrading substances for which the flow to boundary layer is the limiting factor (Eq. 14). Chemical reactions on surfaces were assumed to be oxidation driven by radical species from the air. In addition, reactive chemicals embedded in the surface material could contribute to further reduce the semi-volatile organic compounds in the air, but would have little effect on VOCs.

Fig. 4 Intake fraction as a function of the removal rate due to surface adsorption and degradation: Sensitivity of the intake fraction to different ventilation rate (air exchange rates of 2.04, 0.68 (model), 0.34 h^{-1})

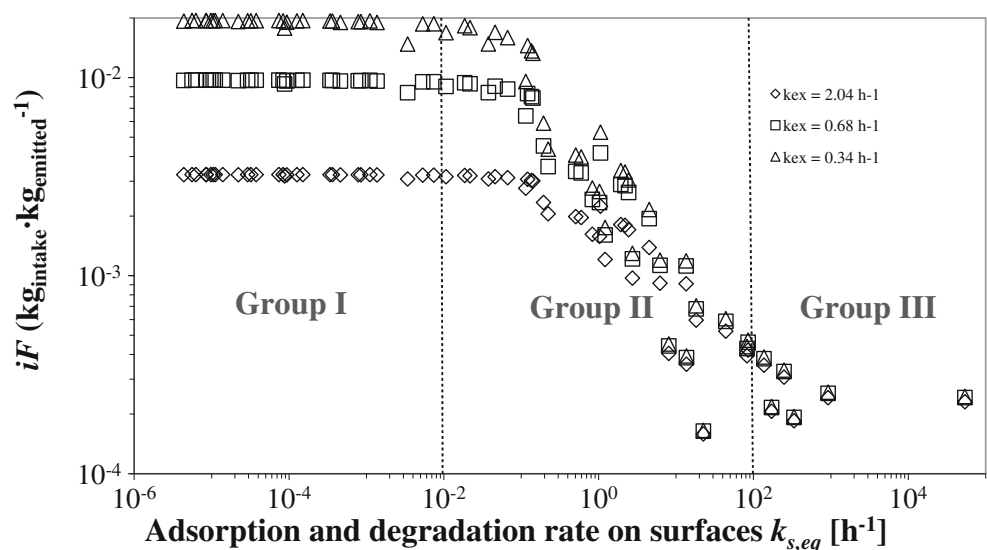
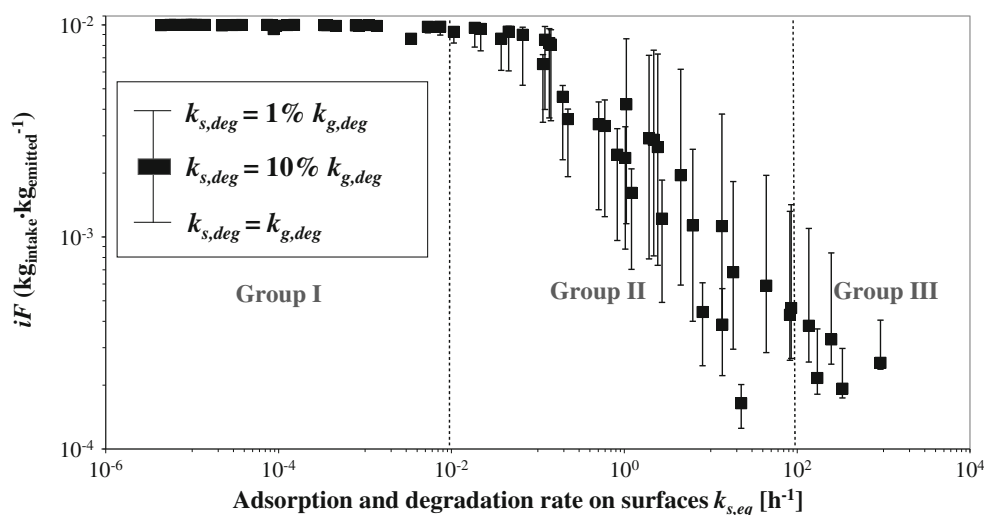


Fig. 5 Sensitivity of the indoor intake fraction to four different surface degradation rates: For $k_{s,deg}^i = 0.01k_{g,deg}^i$, $k_{s,deg}^i = 0.1k_{g,deg}^i$, $k_{s,deg}^i = k_{g,deg}^i$. Chemicals are ordered by increasing $k_{s,eq}^i$ (see Electronic Supplementary Material, supplement S3)



Phase partitioning between gas phase and sorbed to indoor airborne particles: Semi-volatile organic compounds can partition in significant amounts between the surface of indoor airborne particles and the gas phase (Naumova et al. 2003; Weschler 2003). A detailed analysis of particles, such as in Nazaroff (2004), was beyond the scope of the present paper and of the LCA approach. The potential influence of particles on the intake fraction was, however, included by assuming that in the boundary layer, there is an equilibrium between the gas, the surface, and the particles. In this case, the fraction adsorbed to particles compared to chamber surfaces is proportional to the air particle area in the boundary layer per unit surface area; this is a low ratio of $4 \times 10^{-7} \text{ m}_{\text{part}}^2 \text{ m}_{\text{surface}}^{-2}$ for an air particle concentration of $20 \mu\text{g m}^{-3}$ (Weschler 2003). Therefore, the total inhalation intake fractions of the considered compounds were not significantly affected by the presence of air particles. However, the ratio of gas to aerosol intakes varies significantly depending on chemical properties and could potentially affect the chemical bioavailability and the damage to humans (e.g., see Pankow (2001) for a mechanism of human absorption related to tobacco smoke).

5 Conclusions

This study shows that the intake fraction of indoor emissions can be several orders of magnitude higher than outdoor emissions and should not be neglected in LCA practices. At a given ventilation rate, chemicals with different vapor pressures and degradation rates could have great variation in intake fractions. Therefore, considering ventilation rate solely is not sufficient to accurately assess the intake fraction of indoor emissions.

Limitation and perspectives: This approach is mainly valid for long-term behavior, assuming steady state

conditions, which is consistent with the time horizon of 100 years (or infinite time) usually considered in life cycle impact assessment. However, to compare results with experiments in chambers in the case of high adsorption, the period to reach a steady state is rather long and exceeds the common duration of such experiments (generally 1 day versus up to 20 days). Thus, the model should be extended in the future to a dynamic version to enable a full quantitative comparison with experiments. Impacts of dynamics can nevertheless be qualitatively discussed: when emission starts, the concentration at the room surface is 0, and substances entering the boundary layer will tend to be entirely sorbed. In that case, intake fraction will be equal to iF^{min} (Eq. 14, air flux along surfaces as a limiting factor). As concentration on the surface builds up, transfer to the surface is reduced until reaching steady state. The higher the vapor pressure and the lower the degradation rate on the surface, the more time it takes to reach steady state (case of semi-volatile organic compounds).

Several additional parameters have not been treated here but can be of importance. First, *temperature*: most constants used here have been measured at 25°C. Generally, the rates of reaction speed up with temperature. Other factors such as the convection rate or partitioning coefficients may also be influenced. However, indoor environment has relatively stable temperature and its influence would be less significant than other parameters involved in this model. Secondly, *humidity*: for highly water-soluble compounds, such as formaldehyde, sorption to surfaces is anticipated to be affected by the relative humidity and gas phase water can also stabilize intermediary reactions. This situation is very specific and should be evaluated for each chemical independently.

The proposed model demonstrates that relatively low degradation rates on surfaces are sufficient to affect concentration of certain chemicals up to an order of magnitude.

However, most surface experiments are currently performed in relatively inert atmospheres, and little information is available on surface degradation rates. New designs for experiments with controlled ozone, hydroxyl radical, and nitrate radical levels are needed. The fate of a substance shows a clear relationship with its vapor pressure and its partitioning coefficient, allowing researchers to identify which chemicals needed further investigations, namely, substances in group II. To achieve this, we need to further check and extend the range of the empirical relationship between partitioning coefficient and vapor pressure towards lower vapor pressure.

Finally, it must be emphasized that the whole study has focused on indoor exposure in average rooms representing furnished offices or private houses in developed countries with temperate climate. The current model is not suited for occupational health effects of workers directly manipulating and exposed to toxic substances or in a work environment with dedicated ventilation systems, especially where volatile solvents are used and required to have much higher ventilation rates. As described by Hellweg et al. (2009), this situation could be considered as a first approximation by correcting the air exchange rate and introducing a mixing factor that accounts for incomplete mixing.

The model presented in this paper provides a general framework to assess fate and exposure of indoor emissions of chemical compounds, showing the importance of surface sorption. It can be readily integrated in existing LCA models (e.g., USEtox). It is recommended to systematically include the assessment of human health impacts from indoor emissions in future LCA practices.

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References

- ASHRAE (2003) Standard 62–2001 rev. Ventilation for acceptable air quality, add. 62.0
- Atkinson R, Arey J (2003) Atmospheric degradation of volatile organic compounds. *Chem Rev* 103(12):4605–4638
- Axley JW (1991) Adsorption modelling for building contaminant dispersal analysis. *Indoor Air* 1:147–171
- Bennett DH, Margni MD, McKone TE, Jolliet O (2002a) Intake fraction for multimedia pollutants: a tool for life cycle analysis and comparative risk assessment. *Risk Anal* 22(5):905–918
- Bennett DH, McKone TE, Evans JS, Nazaroff WW, Margni MD, Jolliet O, Smith KR (2002b) Defining intake fraction. *Environ Sci Technol* 36(9):206A–211A
- Borazzo JE, Davidson CI, Andelman JB (1990) Sorption of organic vapours to indoor surfaces of synthetic and natural fibrous materials. In: Walkinshaw DS (ed) *Proceedings of indoor air '90*, vol 3. Canada Mortgage and Housing Corporation, Ottawa, pp 617–622
- Coleman BK, Destailats H, Hodgson AT, Nazaroff WW (2008) Ozone consumption and volatile byproduct formation from surface reactions with aircraft cabin materials and clothing fabrics. *Atmos Environ* 42(4):642–654
- Colombo A, Bortoli M, Knoppel H, Pecchio E, Vissers H (1993) Adsorption of selected volatile organic compounds on a carpet, a wall coating, and a gypsum board in a test chamber. *Indoor Air* 3:276–282
- Crettaz P, Pennington D, Rhomberg L, Brand K, Jolliet O (2002) Assessing human health response in life cycle assessment using ED(10)s and DALYs: part 1—cancer effects. *Risk Anal* 22(5):931–946
- Dunn JE, Tichenor BA (1988) Compensating for sink effects in emissions test chambers by mathematical-modeling. *Atmos Environ* 22(5):885–894
- U.S. EPA (1987) Unfinished business: a comparative assessment of environmental problems. Office of Policy, Planning and Evaluation, EPA 230/2-87/025
- U.S. EPA (1990) Reducing risk: setting priorities and strategies for environmental protection. Science Advisory Board, EPA SAB-EC-90-021
- U.S. EPA (1995) Indoor air research: characterizing air emissions from indoor sources. Office of Research and Development, EPA 600/F-95/005
- U.S. EPA (2004) Estimation Programs Interface Suite™ for Microsoft® Windows, v 3.12. United States Environmental Protection Agency, Washington, DC, USA
- Evans JS, Wolff SK, Phonboon K, Levy JI, Smith KR (2002) Exposure efficiency: an idea whose time has come? *Chemosphere* 49(9):1075–1091
- Hellweg S, Demou E, Scheringer M, McKone TE, Hungerbühler K (2005) Confronting workplace exposure to chemicals with LCA: examples of trichloroethylene and perchloroethylene in metal degreasing and dry cleaning. *Environ Sci Technol* 39(19):7741–7748
- Hellweg S, Demou E, Bruzzi R, Meijer A, Rosenbaum RK, Huijbregts MAJ, McKone TE (2009) Integrating human indoor air pollutant exposure within life cycle impact assessment. *Environ Sci Technol* 43(6):1670–1679
- International Standards Organisation (2004) Components and building elements—thermal resistance and thermal transmittance—calculation method (ISO 6946:1996)
- Kikuchi Y, Hirao M (2008) Practical method of assessing local and global impacts for risk-based decision making: a case study of metal degreasing processes. *Environ Sci Technol* 42(12):4527–4533
- Kikuchi Y, Hirao M (2010) Local risks and global impacts considering plant-specific functions and constraints: a case study of metal parts cleaning. *Int J Life Cycle Assess* 15(1):17–31
- Klepeis NE, Nelson WC, Ott WR, Robinson JP, Tsang AM, Switzer P, Behar JV, Hern SC, Engelmann WH (2001) The National Human Activity Pattern Survey (NHAPS): a resource for assessing exposure to environmental pollutants. *J Expo Anal Environ Epidemiol* 11(3):231–252
- Lai ACK, Thatcher TL, Nazaroff WW (2000) Inhalation transfer factors for air pollution health risk assessment. *J Air Waste Manage* 50(9):1688–1699
- Layton DW (1993) Metabolically consistent breathing rates for use in dose assessments. *Health Phys* 64(1):23–36
- Levy JI, Nishioka Y, Spengler JD (2003) The public health benefits of insulation retrofits in existing housing in the United States. *Environ Health* 2(1):4
- Margni M, Pennington DW, Amman C, Jolliet O (2004) Evaluating multimedia/multipathway model intake fraction estimates using POP emission and monitoring data. *Environ Pollut* 128(1–2):263–277

- Marshall JD, Riley WJ, McKone TE, Nazaroff WW (2003) Intake fraction of primary pollutants: motor vehicle emissions in the South Coast Air Basin. *Atmos Environ* 37(24):3455–3468
- Meijer A, Huijbregts MAJ, Reijnders L (2005) Human health damages due to indoor sources of organic compounds and radioactivity in life cycle impact assessment of dwellings—part 1: characterisation factors. *Int J Life Cycle Assess* 10:309–316
- Morrison G (2008) Interfacial chemistry in indoor environments. *Environ Sci Technol* 42(10):3494–3499
- Naumova YY, Offenberg JH, Eisenreich SJ, Meng QY, Polidori A, Turpin BJ, Weisel CP, Morandi MT, Colome SD, Stock TH, Winer AM, Alimokhtari S, Kwon J, Maberti S, Shendell D, Jones J, Farrar C (2003) Gas/particle distribution of polycyclic aromatic hydrocarbons in coupled outdoor/indoor atmospheres. *Atmos Environ* 37(5):703–719
- Nazaroff WW (2004) Indoor particle dynamics. *Indoor Air* 14:175–183
- Nazaroff WW, Weschler CJ (2004) Cleaning products and air fresheners: exposure to primary and secondary air pollutants. *Atmos Environ* 38(18):2841–2865
- Pankow JF (2001) A consideration of the role of gas/particle partitioning in the deposition of nicotine and other tobacco smoke compounds in the respiratory tract. *Chem Res Toxicol* 14(11):1465–1481
- Pennington D, Crettaz P, Tauxe A, Rhomberg L, Brand K, Jolliet O (2002) Assessing human health response in life cycle assessment using ED(10)s and DALYs: part 2—noncancer effects. *Risk Anal* 22(5):947–963
- Pennington DW, Margni M, Ammann C, Jolliet O (2005) Multimedia fate and human intake modeling: spatial versus nonspatial insights for chemical emissions in Western Europe. *Environ Sci Technol* 39(4):1119–1128
- Pommer L (2003) Oxidation of terpenes in indoor environments: a study of influencing factors. PhD Thesis, Umeå University, pp 84
- Pommer L, Fick J, Nilsson C, Andersson B (2004) An experimental comparison of a kinetic model for the reaction of α -pinene and Δ^3 -carene with ozone and nitrogen oxides. *Indoor Air* 14:75–83
- Renes S, Leaderer BP, Schaap L, Verstraelen H, Tosun T (1985) An evaluation of sink terms in removing NO₂ and SO₂ from indoor air. In: Fanger PO (ed) CLIMA 2000: proceedings of the world congress on heating, ventilating and air-conditioning, vol 4. Copenhagen, Denmark, pp 221–226
- Rosenbaum R, Huijbregts M, Henderson A, Margni M, McKone T, van de Meent D, Hauschild M, Shaked S, Li DS, Gold L, Jolliet O (2011) USEtox human exposure and toxicity factors for comparative assessment of toxic emissions in life cycle analysis: sensitivity to key chemical properties. *Int J Life Cycle Assess* 16:710–727
- Sanchez DC, Mason M, Norris C (1987) Methods and results of characterization of organic emissions from an indoor material. *Atmos Environ* 21(2):337–345
- Seifert B, Schmahl H (1987) Quantification of sorption effects for selected organics substance present in indoor air. *Proceedings of Indoor Air' 87*. Vol 1, pp 252–256
- Singer BC, Hodgson AT, Guevarra KS, Hawley EL, Nazaroff WW (2002) Gas-phase organics in environmental tobacco smoke. 1. Effects of smoking rate, ventilation, and furnishing level on emission factors. *Environ Sci Technol* 36(5):846–853
- Tichenor BA, Guo Z, Dunn JE, Sparks LE, Mason MA (1991) The interaction of vapour phase organic compounds with indoor sinks. *Indoor Air* 1:23–35
- Weschler CJ (2003) Indoor/outdoor connections exemplified by processes that depend on an organic compound's saturation vapor pressure. *Atmos Environ* 37(39–40):5455–5465
- Weschler CJ, Nazaroff WW (2008) Semivolatile organic compounds in indoor environments. *Atmos Environ* 42(40):9018–9040
- Weschler CJ, Wisthaler A, Cowlin S, Tamas G, Strom-Tejsten P, Hodgson AT, Destailats H, Herrington J, Zhang JJ, Nazaroff WW (2007) Ozone-initiated chemistry in an occupied simulated aircraft cabin. *Environ Sci Technol* 41(17):6177–6184
- Won DY, Corsi RL, Rynes M (2000) New indoor carpet as an adsorptive reservoir for volatile organic compounds. *Environ Sci Technol* 34(19):4193–4198
- Won D, Corsi RL, Rynes M (2001) Sorptive interactions between VOCs and indoor materials. *Indoor Air* 11(4):246–256
- Zhou Y, Levy JI, Hammitt JK, Evans JS (2003) Estimating population exposure to power plant emissions using CALPUFF: a case study in Beijing, China. *Atmos Environ* 37(6):815–826